Plasma assisted tunable THz radiation source

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Aim of the project

The aims of the research project are
1/ to produce fs-micro-bunch trains from a long (ps) electron beam using plasma channel ;
2/ to generate tunable coherent THz radiation using the micro-bunch train;
3/ to monitor micro-bunch train frequency using coherent SP/Cherenkov radiation

Project layout

Part 1: *Plasma assisted pre-buncher with tunable plasma density to generate micro-bunch train. Measurement of micro-bunch train periodicity as function of plasma density using: interferometer, cSPr and cChr.*

Part 2: *Generation of THz radiation using periodic structures/dielectric material and pre-bunched electron beam. Demonstration of THz source tunability with change of the plasma density.*

Project: beam requirements

- Beam parameteres:

single particle energy - 50MeV;

total beam charge - 0.5 nC;

beam length - 1.5 mm (5ps);

beam transverse $\boldsymbol{\sigma}_r$ - 80 μm;

beam longitudinal profile - trapezoidal with equal (50 μm/0.17ps) rise\decay/ slopes\times (i.e. much shorter as compared with plasma wavelength)

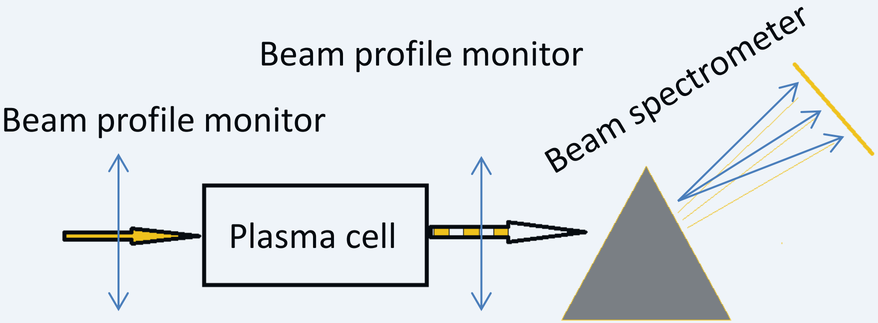
Project: instruments

1/ Experimental Chamber with plasma source and Multiple viewing ports and motorized in-vacuum translations
(if there is no plasma channel we can use we will make it)

2/ Beam Diagnostics: beam profile monitors; electron beam spectrometer; streak and IR cameras; cTr foil and Michelson Interferometer

Project: experiments

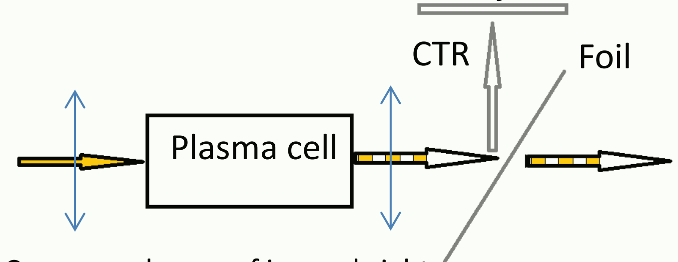
a/ *wakefield excitation and energy modulation*



Expected energy variation 1% due to wakefield interaction (S. Antipov et al., PRL,112, 114801 (2014))

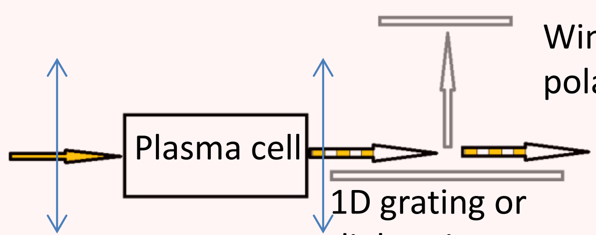
b/ *image generated by optical CTR with and without beam modulation*

IR, Streak Cameras, M. Interferometer



Cameras: change of image brightness
Michelson interferometer: temporal structure of micro-bunch (S. Antipov et al., PRL 111, 134802 (2013)

c/ *measurement of THz signal at micro-bunch modulation frequency*



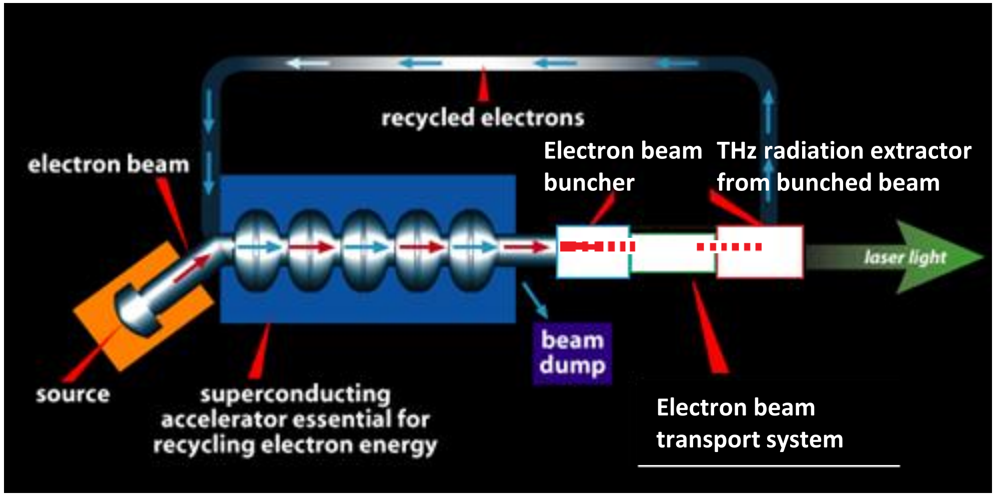
Winston cone with filter, polarizer and detector

1D grating or dielectric structure

We expect to see spectra with the line at plasma frequency and width ~ω_p/N

Motivation

1/ Tunable THz source

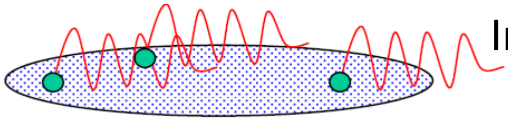


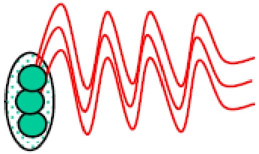
Coherence is insured by either installing a cavity or via pre-bunching electron bunch making its dimensions smaller as compared with operating wavelength.

$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e} = \left(\frac{dI}{d\Omega d\omega}\right)_{sp} \cdot [N_e + N_e(N_e - 1)|F(\omega)|^2]$$

Incoherent radiation

Coherent radiation





2/ Micro-bunch profile monitor

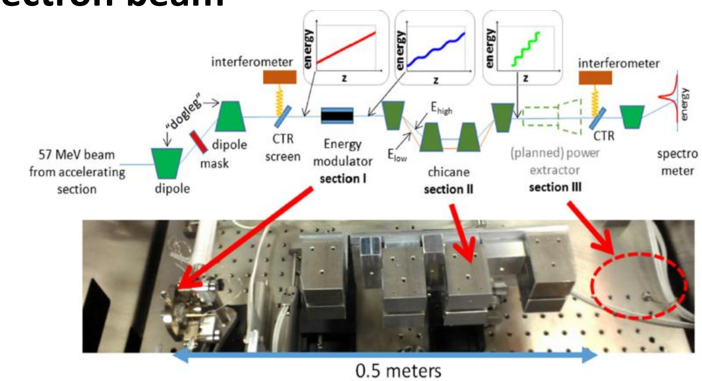
Beam modulation

1/ Direct modulation of bunch using photocathode and fs laser A. Aryshev et al., KEK

+ No loss of electron beam, the micro-bunch repetition frequency can be controlled and thus frequency of the generated radiation THz
- Laser system can be complicated to generated long train of micro-bunches

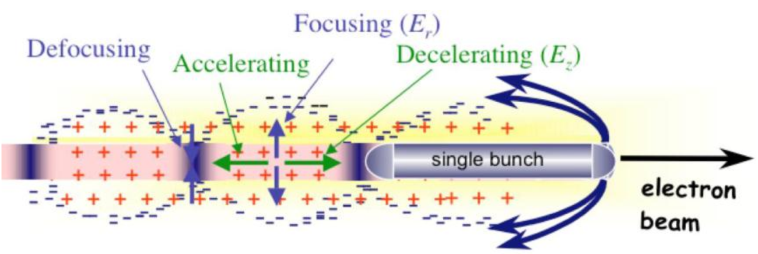
2/ Sub-picosecond Bunch Train Production via wakefield energy modulation in dielectric lined structure - *S. Antipov et al., Phys. Rev. Lett. 111, 134802 – Published 25 September 2013*

+ relatively short and simple system
- modulation via electron beam cuts => loss of electron beam



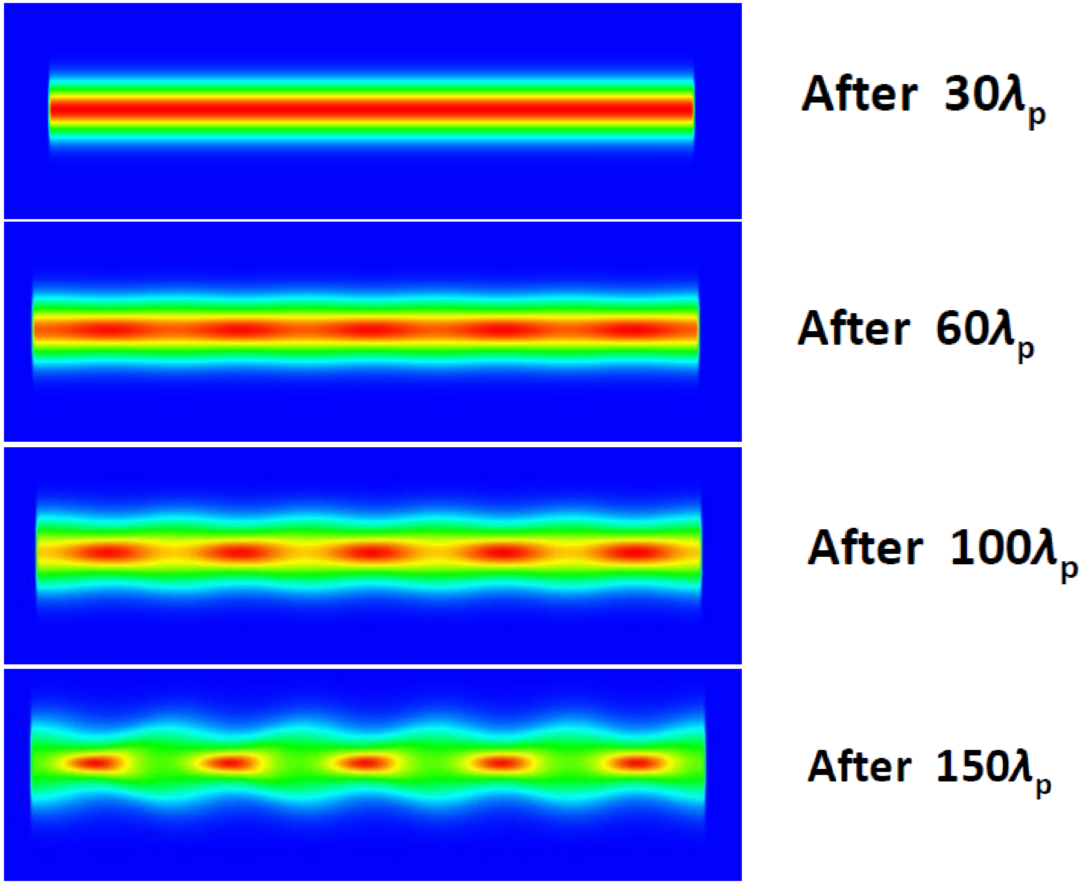
3/ Beam modulation inside plasma channel via transverse instability (AWAKE)

+ short and relatively simple system
+ tuneable via plasma density
- dealing with plasma



Plasma Beam modulation

Plasma density: $n_p = 1.3 \times 10^{16}$ cm^{-3} ; $\lambda_p = 300 \mu m$ (1THz)
Electron beam density: $n_b = 2 \times 10^{13}$ cm^{-3}, Gaussian transverse profile and uniform longitudinal distribution

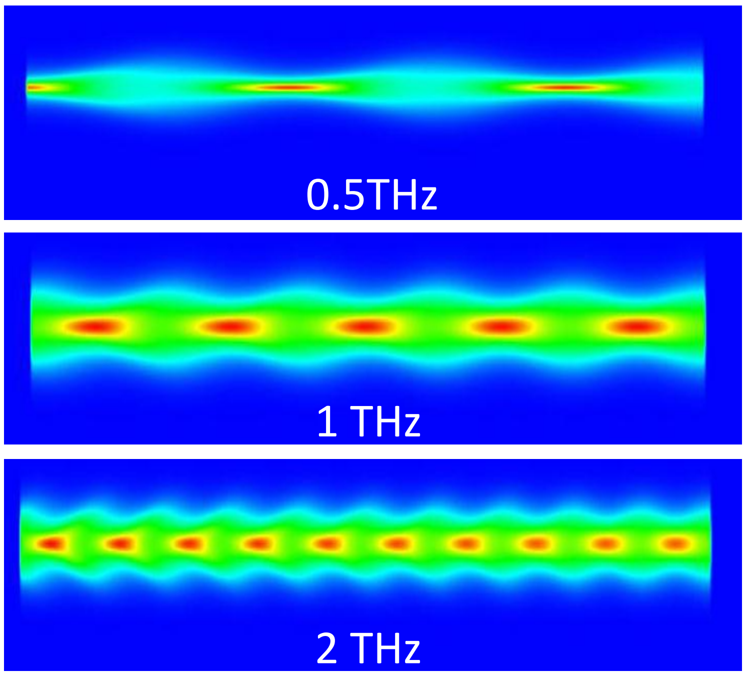


Simulation of electron beam modulation inside plasma channel using 3D PiC code VSim (Mr. Huibo Zhang, PhD)

Tunability of beam modulation

Simulation of electron beam modulation inside plasma channel using
3D PiC code VSim (Mr. Huibo Zhang, PhD)

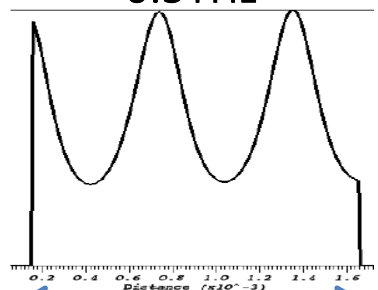
Beam modulation after passing
through a 5cm capillary



Plasma density

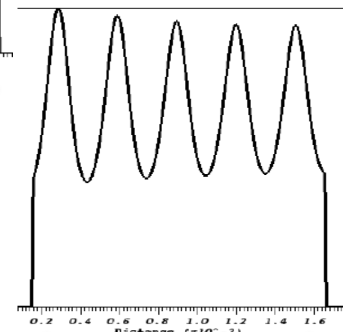
1) $n_p = 3.25\times10^{15}/cm^3$, λ_p = 600 um, *f=0.5 THz*
2) $n_p = 1.3\times10^{16}/cm^3$, λ_p =300 um, *f=1 THz*
3) $n_p = 5.2\times10^{16}/cm^3$, λ_p = 150 um, *f=2 THz*

0.5THz



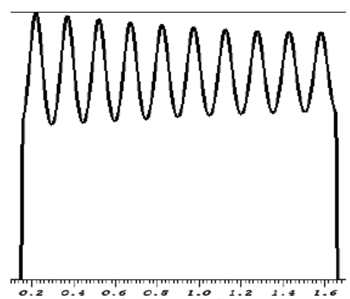
1.5cm

1.0 THz



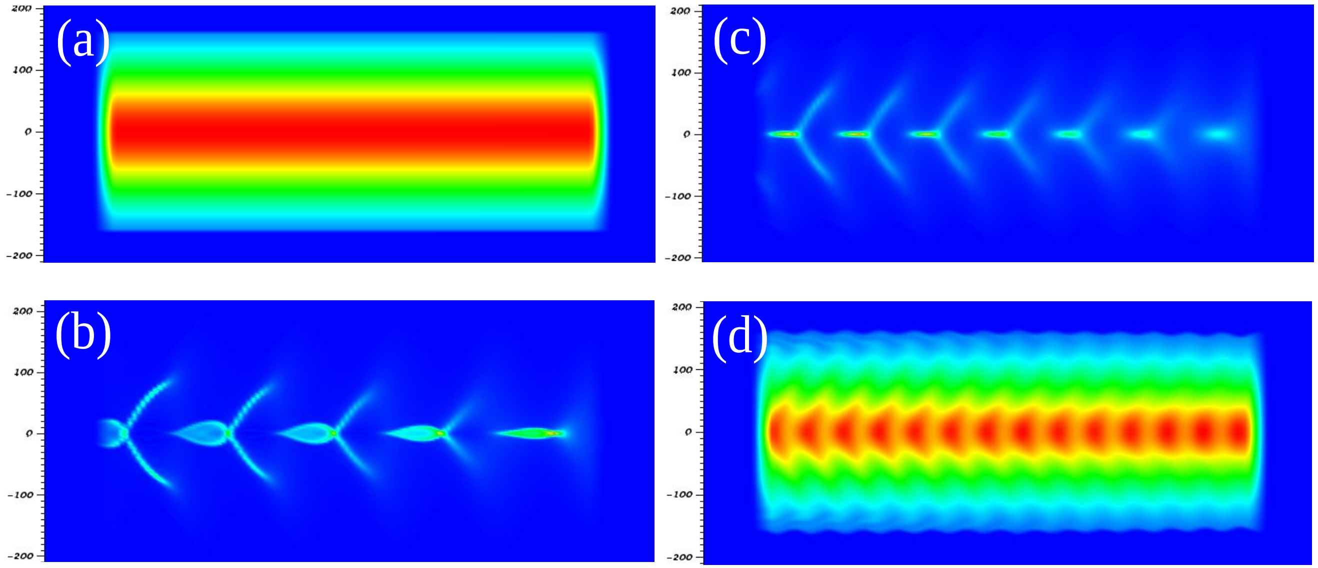
1.5cm

2.0 THz



1.5cm

Tunability of beam modulation



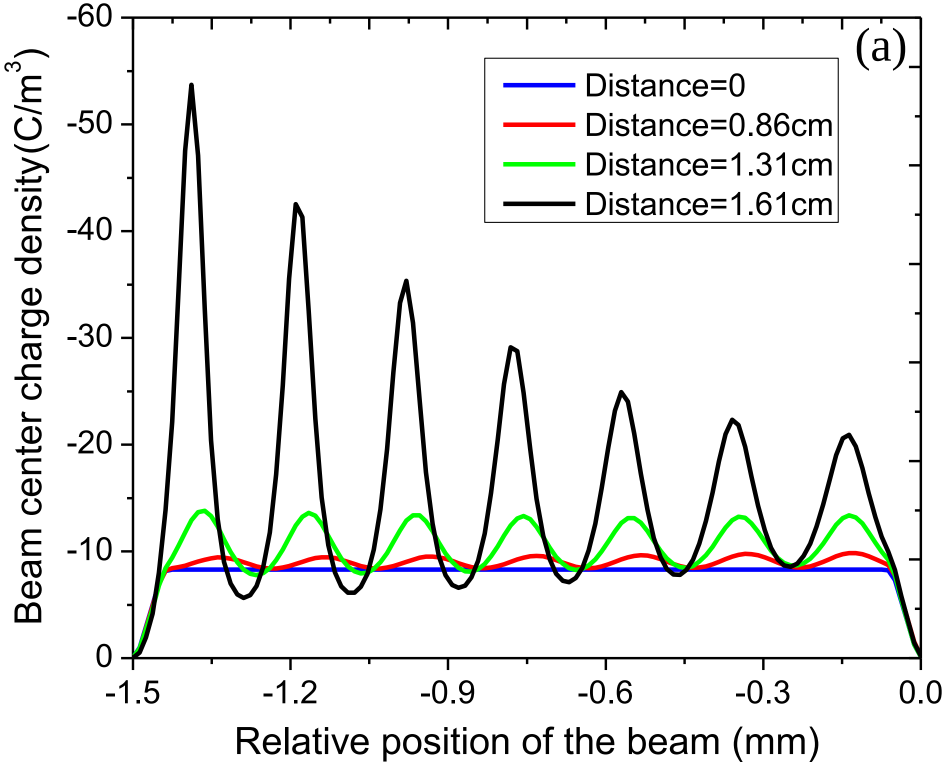
Beam density distribution versus plasma density.

(a) Initial beam distribution;

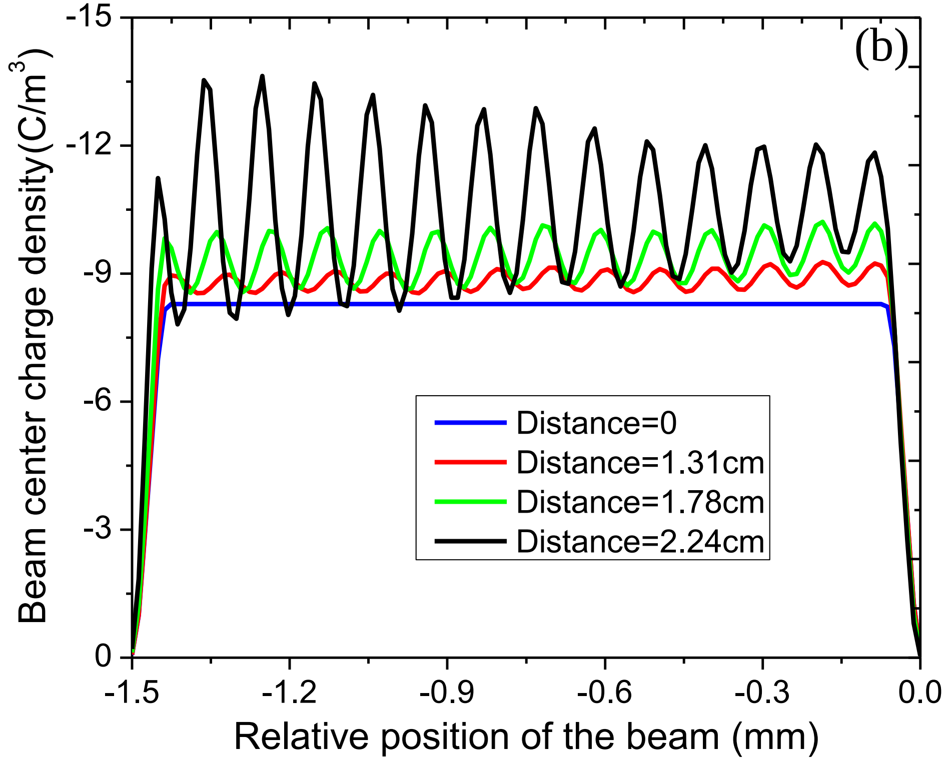
(b)-(d) Beam density distribution after propagating 1.8 cm with plasma density of $1.24\times10^{22}/m^3$, $2.84\times10^{22}/m^3$ and $1.12\times10^{23}/m^3$ respectively, the corresponding plasma wavelength is 300 μm, 200 μm and 100 μm.

Tunability of beam modulation

λ_p=200um



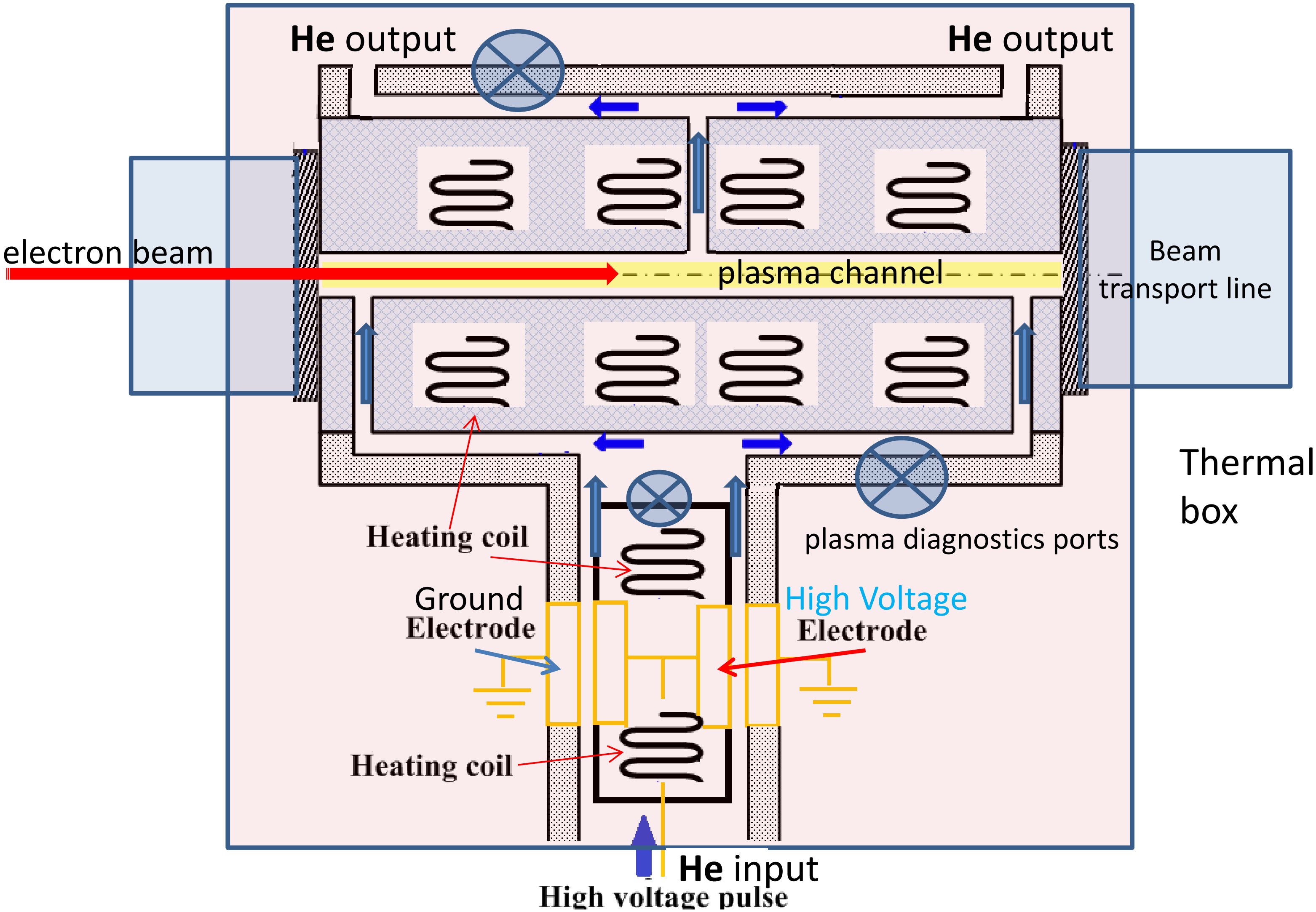
λ_p=100um



The beam charge density on axis along the beam versus propagation distance

(beam energy is 50MeV, charge is 0.5 nC, beam length is 1.5 mm, beam transverse σ_r is 80 µm. The beam longitudinal rise profile is in linear, and the rise-time is 50 µm)

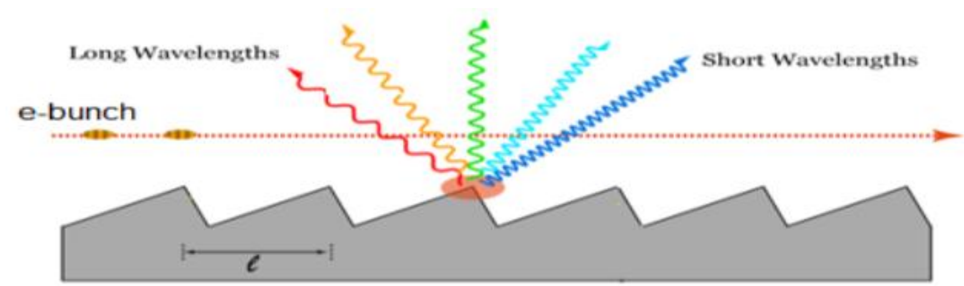
Schematic of plasma cell

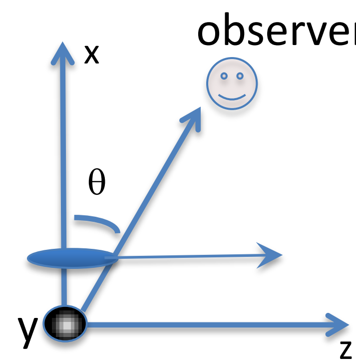


Smith-Purcell radiation

$$\lambda = \frac{\ell}{m}\left(\frac{1}{\beta} - \cos\theta\right)$$

Dispersion relation links radiated wavelength and observation angle θ





$$\left(\frac{dI}{d\Omega}\right)_{sp} = F\exp\left(-\frac{2x_0}{\lambda_e}\right)$$

$$\lambda_e = \frac{\lambda}{2\pi}\frac{\beta\gamma}{\sqrt{1+\beta^2\gamma^2\sin^2\theta\sin^2\phi}}$$

1/ x_0 is the distance between beam and the periodic structure
2/ λ_e is the electron beam - EM wave coupling parameter
3/ further electron beam is away smaller energy transfer to EM wave

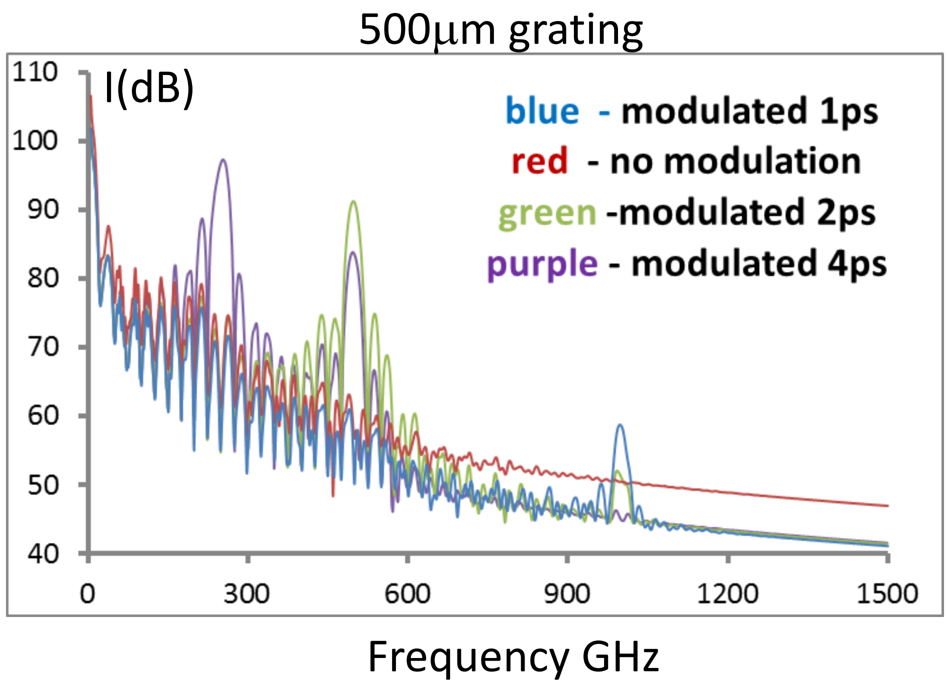
For small θ and φ such that
$(\theta\varphi) \ll 1/\gamma$

$$\lambda_e = \frac{\lambda\gamma\beta}{2\pi}$$

10MeV beam should be 0.1mm away to generate radiation at 10THz

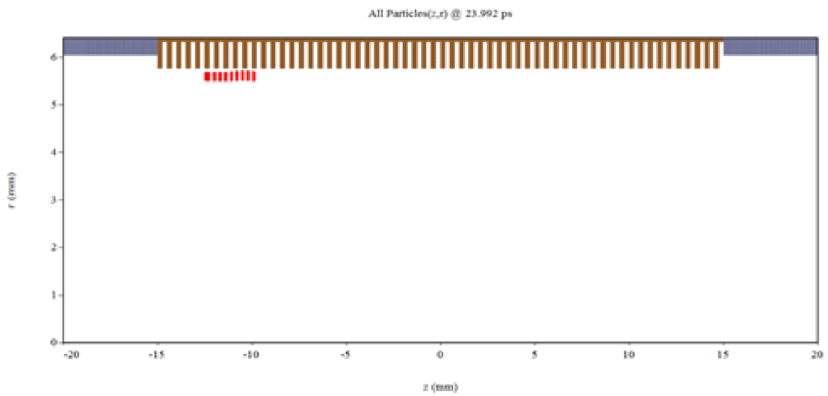
Interaction with micro-bunch train

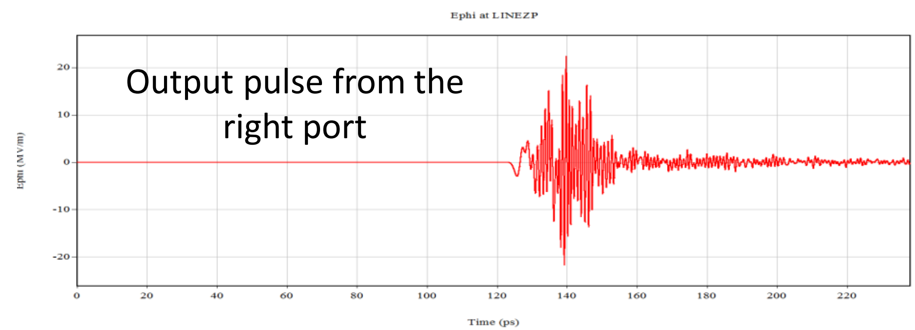
SP signal spectra from the beams with
No modulation; 1ps; 2ps; 4ps

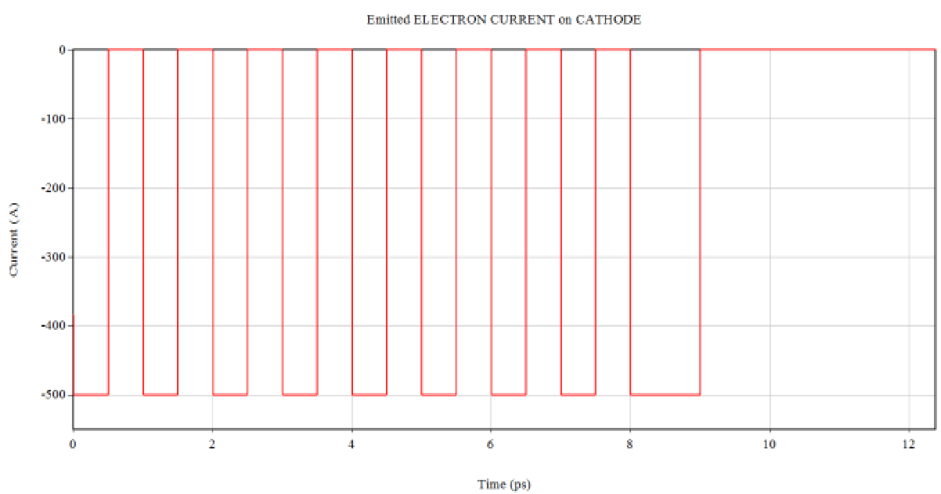


Signal strength is sufficient to measure

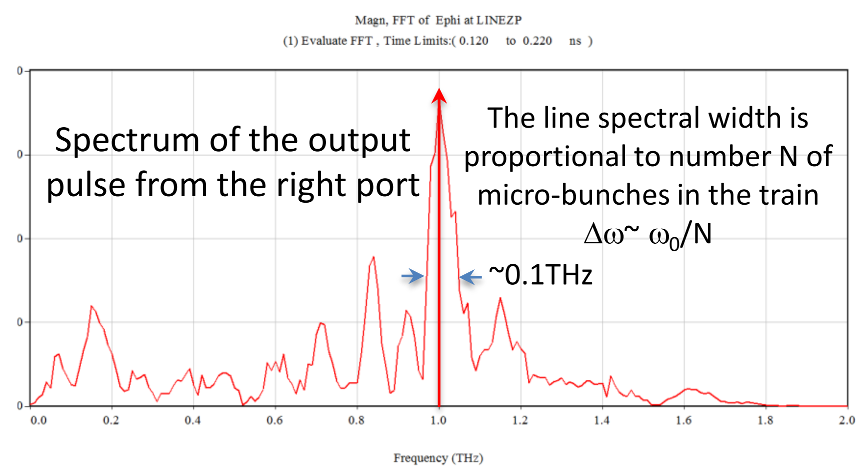
THz Radiation from a micro-bunch train





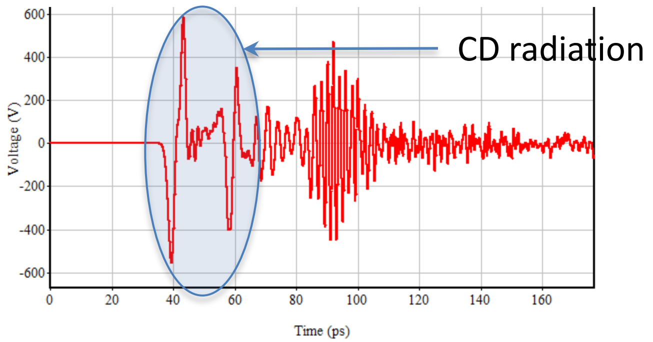


9 Micro-bunches were generated

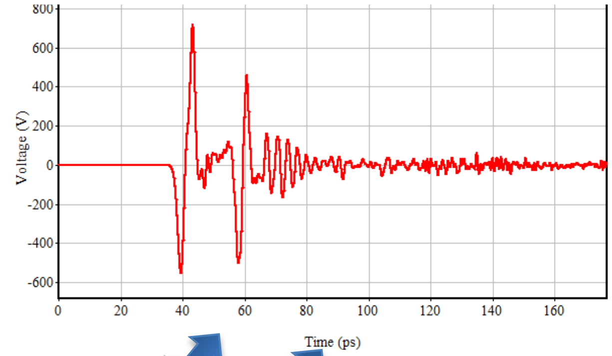


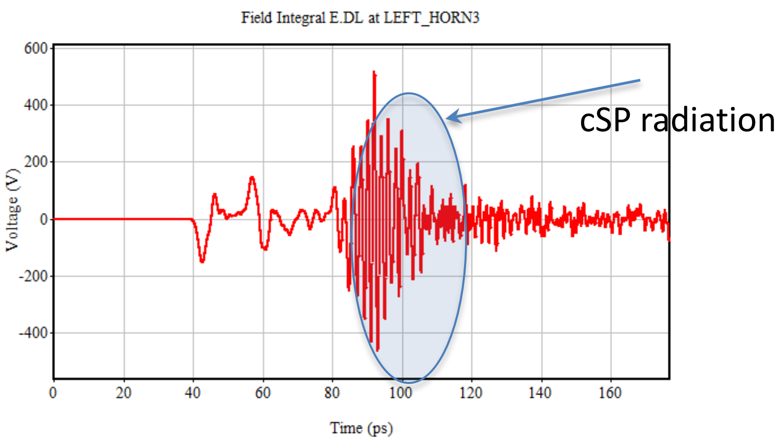
Numerical model

Signal measured along full length L of the radiating aperture

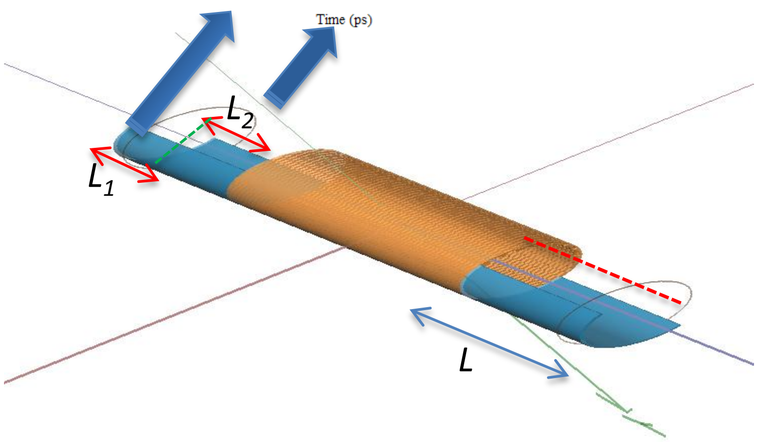


Signal measured along first part L_1 of the radiating aperture

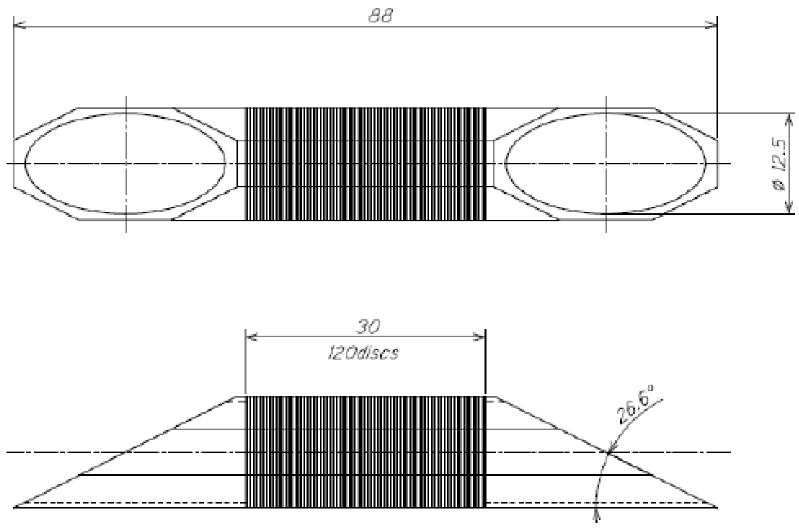


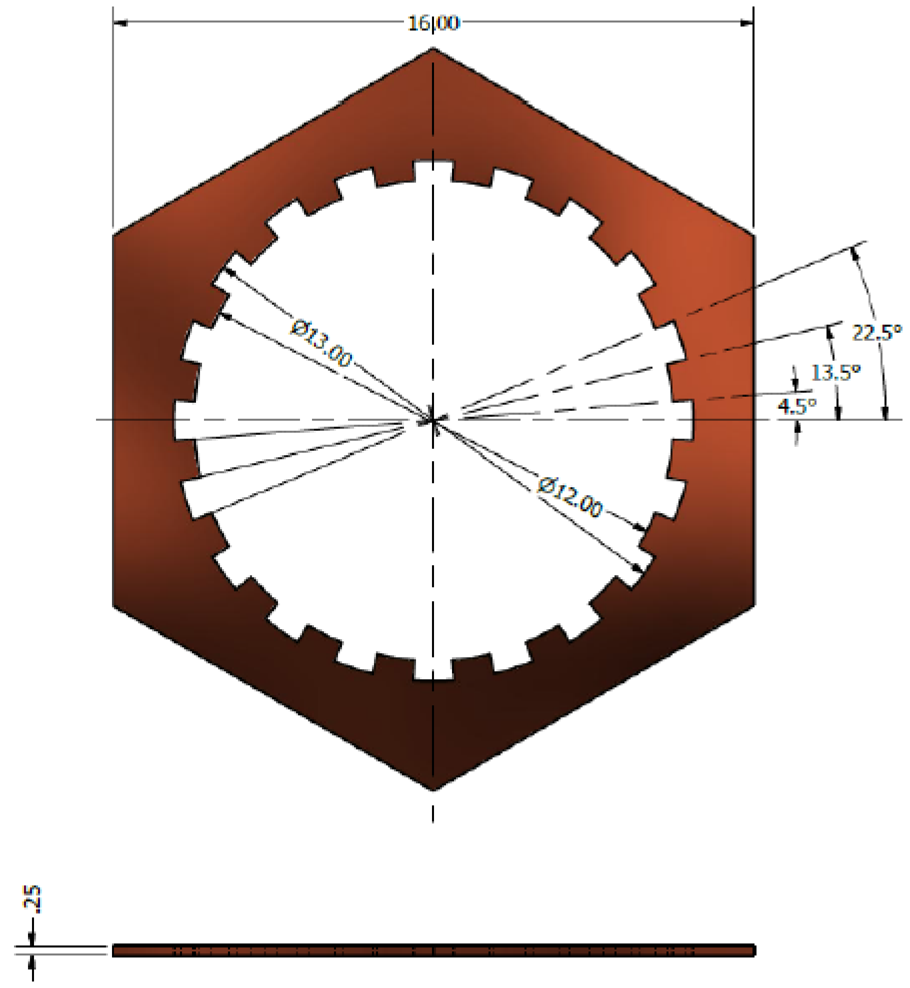


Signal measured along first part L_2 of the radiating aperture

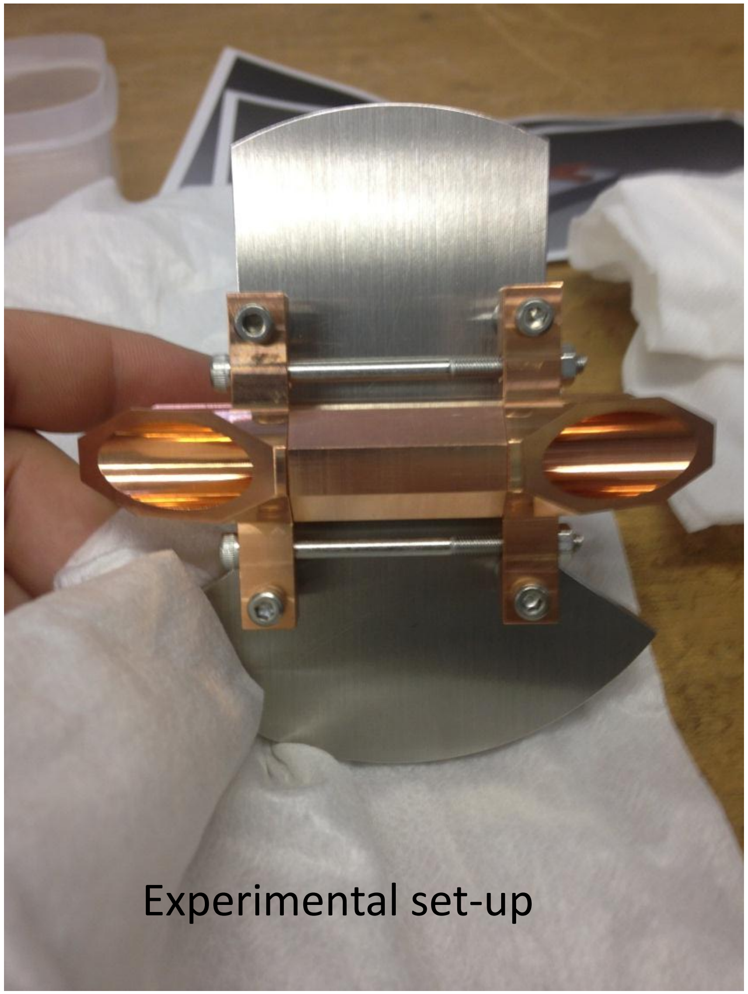


Manufacturing

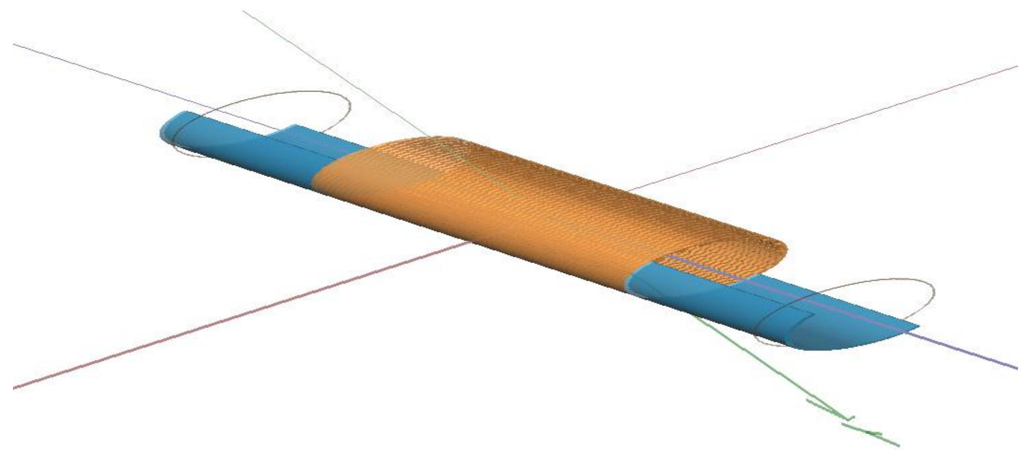




Blanc cylindrical waveguide with Vlasov outputs



Numerical model



Thank you